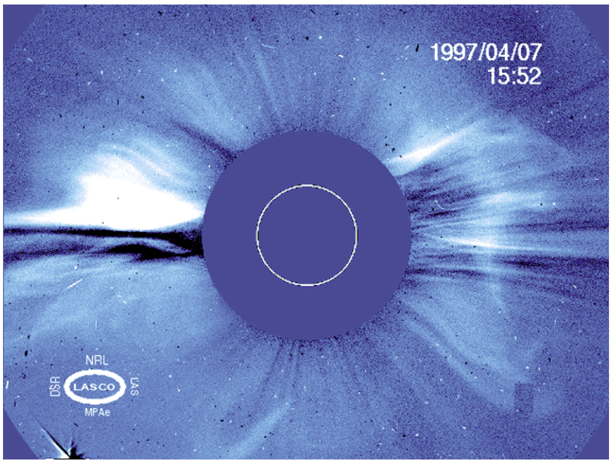
Solar–Terrestrial Connection: Space Weather Predictions

'Space weather' refers to the dynamic state of the magnetosphere and ionosphere, which is determined by the SOLAR WIND. Interest in the ability to predict space weather, and its effects on Earth, really began during World War II. For the first time, electronic technologies, such as radars and radio communications, were heavily relied on, and it soon became clear that these technologies could be seriously disrupted by solar activity. After the war, more uses were developed for electronic technologies, including the start of the space program. Since then, our need to be able to forecast solar activity has continued to increase as technology becomes more widespread. Under disturbed conditions, satellite- and ground-based technological systems, e.g. communications networks, electric power grids and satellites, can suffer harmful effects. Such systems are particularly vulnerable during severe GEOMAGNETIC STORMS. Large storms are relatively infrequent but, when they occur, they can stress the susceptible systems for prolonged periods of time over large geographic areas. Secure operation of systems can still be maintained and hazards can be minimized if the occurrence, duration and severity of impending storms can be accurately predicted in a timely manner. Thus, space weather forecasting is important for protecting national assets in both the commercial and military sectors.

In the early days of solar forecasting, it was assumed that when a large FLARE occurred on the Sun there would be a very predictable geomagnetic disturbance on Earth within a few hours or days. Later it was realized that it was the SOLAR CORONAL MASS EJECTIONS (CMEs) that had a greater effect on Earth. It was therefore believed that improved forecasting was just a matter of making better observations of the Sun so that flares and CMEs could be detected immediately after they occurred. Experience, however, soon showed that the effects on Earth did not correlate so simply with events on the Sun and, moreover, not all mass ejections had a noticeable effect on Earth. Sometimes geomagnetic storms occurred when there was no apparent eruptive activity on the Sun. We now know that how the Sun's magnetic field connects with the geomagnetic field makes a big difference in how solar activity affects Earth. When a mass of PLASMA is ejected from the Sun, the plasma travels outward in the solar wind. These plasma bursts have their own magnetic fields, which are carried along with the plasma. How these fields are oriented when they arrive at Earth determines whether or not the event will be effective. When the direction of the solar wind field is opposite the direction of Earth's field, MAGNETIC RECONNECTION occurs, and the magnetosphere essentially becomes joined to the solar magnetic field. In this condition, Earth is much more prone to the effects of the solar wind. Solar wind particles can enter the magnetosphere more easily, and those already within the magnetosphere are energized. If the magnetic field of the solar wind is in the same direction as the Earth's field, then magnetic reconnection does not occur and the magnetosphere is much more separated and protected from the solar wind. Under these conditions, the effects of CMEs are much less significant. In order to know what is going to happen on Earth it is important to know not only what happened on the Sun but also the characteristics of the magnetic fields that are carried along with the solar wind. Accurate forecasts of large storms are difficult to achieve because the propagation of solar disturbances to the Earth and magnetic field characteristics are difficult to predict with high accuracy. Using the solar wind and interplanetary magnetic field quantities measured upstream from the Earth as input, however, can warn of the impending arrival of solar wind structures and, therefore, predict their geoeffectiveness, that is to say, their effect on the Earth. Forecasters have reviewed large amounts of historical solar wind data and have found that they can identify and predict the occurrence of large storms, with accuracy in the range 70–80%.



(*a*)

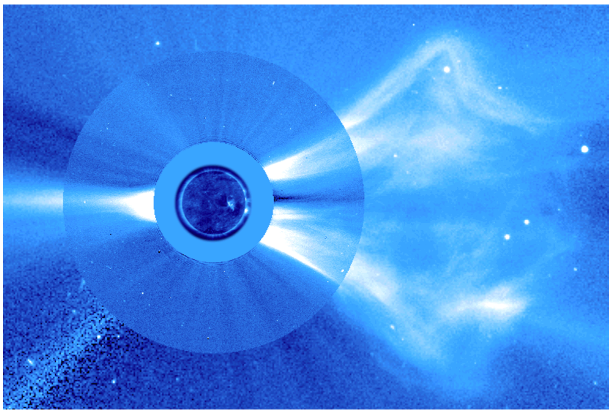


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Figure 1. Coronagraph observations of the solar corona from the SOHO spacecraft: (*a*) shows a clear halo CME propagating away from the Sun and (*b*) shows a limb event.

Recently, a number of spacecraft have been launched

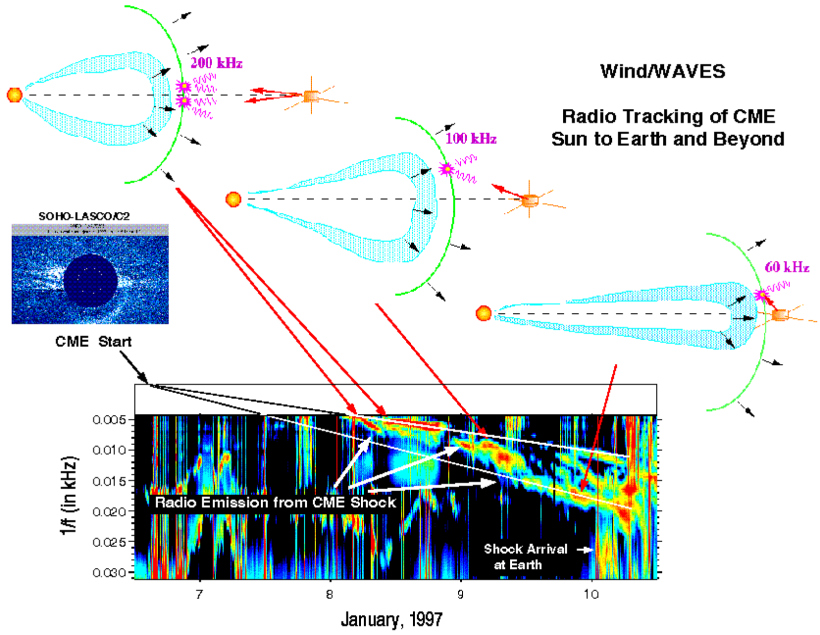

Figure 2. Dynamic spectra of radio data taken by the WIND spacecraft during 6–11 January 1997 in the frequency range 23–245 Hz. Radio emissions from the CME shock are marked on the figure and decrease in frequency as the CME moves further from the Sun. The cartoon above the spectrogram represents the progress of the CME as it expands away from the Sun towards the WIND spacecraft located about half a million miles in front of the Earth.

which have improved our ability to forecast space weather disruptions. SOHO (Solar and Heliospheric Observatory), a joint NASA (National Aeronautical and Space Administration) and ESA (European Space Agency) mission, provides near-real-time images of the Sun and its CORONA, clearly showing ACTIVE REGIONS, flares and CMEs. Events occurring on the side of the Sun—the limb—are regularly seen which will not affect the Earth. Sometimes, however, CMEs occur on the side of the Sun facing Earth. These events appear to be very different when viewed from Earth. Instead of looking like a 'bubble' of plasma, they form a circle of light around the Sun. This light is much dimmer than the Sun itself, so it is necessary to put an occulting disk in front of the Sun in order to see what goes on around it—like an artificial solar eclipse. The instrument used to do this is called a CORONAGRAPH. An example of such a 'halo' event is shown in figure 1, together with one occurring on the limb for comparison.

The faster CMEs have outward speeds of up to 2000 km s^{-1}, considerably greater than the normal solar wind speeds of about 400 km s^{-1}. These produce large shock waves in the solar wind as they plow through it, much like a jet breaking the sound barrier drives a sonic boom into the atmosphere. In the case of the CME shock, however, the sonic boom takes the form of very intense, low-frequency radio emissions known as solar type II bursts. (Instruments on Earth cannot detect the type II bursts because the ionosphere blocks the waves. Only a radio receiver in space can detect them.) As the shock approaches Earth, these type II bursts drift down in frequency (see figure 2) because the electron density of the interplanetary medium to which the solar bursts are 'tied' is also constantly decreasing. Space-borne instruments are capable of detecting these radio bursts from a great distance, long before the CME arrives at Earth. These radio receivers can also determine the direction from which the waves are arriving. Combined with the known propagation speed of the shock, this information allows forecasters to track the CME shock front nearly from the time that it is no longer visible to the solar telescopes, all the way to Earth. Finally, as mentioned above, it is critical to have a satellite between the Sun and Earth so that the nature of the solar wind can be observed before it arrives. In August of 1997, NASA launched ACE, the Advanced Composition Explorer satellite, which is located a million miles upstream of the Earth. This location allows ACE to detect the Earth-directed solar wind about 1 h before it impacts us.

The NOAA Space Environment Services Center (SESC) in Boulder is one of the world centers making forecasts of solar and geomagnetic activity (see figure 3). Daily predictions are issued for the likelihood of solar flares, proton flares, x-ray events and magnetic storms. Longer-range forecasts are also made so that the launches of manned space flights can be planned with more safety. The SESC receives about 1400 data streams daily, including x-ray and particle flux data from the GOES satellites, Hα images and magnetograms from observatories around the world, measurements of the geomagnetic field at many locations, and 10.7 cm radio levels from several

Figure 3. The new NOAA Space Environment Forecast Center. In a similar manner to meteorologists checking temperatures, winds and pressure to predict the weather on Earth, scientists monitor the Sun and the space environment to help forecast space weather.

radio telescopes. Each day the features of the solar disk are mapped by hand so that the evolution of active regions, coronal holes, filaments, and neutral lines may be carefully studied. Forecasters attempt to consider all of this information when making their daily forecasts of solar effects on Earth. At the present time, these forecasts are not very reliable; major flares are sometimes not forecast and predictions that are made often do not come true. Even though forecasters have a large amount of data to work with, the physics of the Sun, the magnetosphere and the interplanetary medium is not well understood. At the present time, many partial mathematical models have been developed, but there is no comprehensive model of the solar–terrestrial environment.

In most cases, the ability to predict the behavior of nature comes from a mathematical model. Earth weather forecasters have been trying for the last 30 yr to construct a mathematical model of the global weather using the very complex equations of fluid dynamics to describe the circulation of the oceans and atmosphere. Even with the best supercomputers to run these models, it has proven impossible to precisely model Earth weather. Modeling the solar–terrestrial environment is vastly more complex. The physics necessary to do this includes not only fluid dynamics but also Maxwell's equations. This combination is known as MAGNETOHYDRODYNAMICS (MHD), and at the present time the equations of MHD cannot be completely solved analytically.

Research to improve solar forecasting is occurring in three major areas. The *first* is improving the basic understanding of the way in which eruptions from the Sun occur, namely of prominence eruptions and CMEs. In particular, a workable two-dimensional model of the way a coronal arcade loses equilibrium and erupts as an MHD catastrophe is being developed into a three-dimensional model. Also, models are being developed for the three-dimensional evolution of coronal structures before they erupt. The *second* area is the correlation of observable phenomena with effects on Earth. For example, a strong correlation has been observed between sunspot cycles and disturbances on Earth. However, this correlation is very coarse; it is known that during a certain period of years there will be high levels of solar activity and accompanying disturbances on Earth. It is not yet possible to accurately predict these disturbances as happening over specific days or hours. Many researchers are trying to refine the correlations between observable symptoms, such as increased radio emission, and subsequent eruptions of mass. Some of the best correlations yet are those that have been found between the evolution of sunspot groups and eruptions.

The *third* area of work is that of constructing a model for the solar–terrestrial environment. In addition to the complexities of MHD, the problem is difficult because there are three different domains involved, which all couple together. The first domain is that of the Sun; to simply construct a mathematical model of the Sun is far beyond researchers at the present time. There are still many mysteries about what processes occur inside the Sun, what triggers flares and even why sunspots form. The second domain is the interplanetary medium, once thought of as empty space. This space is filled with the solar wind plasma, which is not fully understood. The third domain is the Earth's magnetosphere, with its many regions and currents. The magnetotail, extending for millions of kilometers out from Earth, has been difficult to study directly and remains poorly understood. Models for any one of these domains by themselves are not even close to completion, but the final complication arises because these three domains are not at all separate. A change in one of these domains can have major consequences on the Earth. Scientists and forecasters alike continue to analyze misses and false alarms in detail to better understand the performance characteristics of the prediction methods, and a number of improvements have been developed to deal with the known failure modes. It is hoped that one day there will be a comprehensive model for the entire solar–terrestrial environment but this is certainly a problem for physicists of the future. Forecasters will continue to make forecasts based on present knowledge and available data, and hopefully the forecasting ability will continue to improve. The physics of the solar–terrestrial environment is still one of the great frontiers, awaiting new generations of scientific explorers.

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